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USING ATOM OPTICS TO FABRICATE NANOSTRUCTURES

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1. Introduction

The drive for further miniaturization of electronic and magnetic devices continues to place increasing demands on our abilities to fabricate very small structures and to understand and exploit the physical laws applicable in such devices. Optical lithographic techniques continue to be refined and limitations imposed by diffraction are driving the wavelength of the photons utilized toward the x-ray region. Still shorter wavelength particles, high energy electrons, are used for the highest resolution mask making. A logical extension of this progression would involve using atoms, because of their short de Broglie wavelength, as the pattern generating particle, either to expose a resist, or to deposit structures directly. We are exploring how the techniques of atom optics, a field paralleling electron optics but utilizing neutral atoms instead of electrons, can be used to fabricate structures on the nanometer scale. This article is a brief summary of our research on this topic. A more detailed treatment can be found elsewhere [1].

2. Background

Since external fields were used to deflect neutral atom beams by Stern and Gerlach [2] in the early 1920's, research employing atom optics has a long and venerable history. However, the field was revitalized when it was realized that lasers could be used to produce a spatial distribution of electric fields that interact with and deflect free atoms. In 1978, Bjorkholm et al [3] demonstrated the focusing and defocusing of an atom beam using a spatially varying laser intensity. In 1987, Balykin and Letokhov [4] suggested that the use of a special cylindrically symmetric laser mode for focusing might permit very high spatial resolution to be obtained. Theoretical treatments by McClelland and Scheinfein [5], as well as Gallatin and Gould [6] showed in 1991 that laser focusing of atoms to a resolution of a few nanometers might be possible. Subsequently, Sleator et al [7] demonstrated focusing of metastable He atoms by a standing wave. In 1992, Timp et al [8] used a standing wave geometry to deposit Na on a substrate and showed the resulting structure to be periodic through optical diffraction measurements. Finally, in 1993, McClelland et al [1] fabricated and imaged Cr structures on a Si substrate.

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3. Method

Neutral atoms passing through the radiation field of a laser can be deflected by forces of two types. The first is simply due to the radiation pressure; atoms absorb directed photons (and directed momentum) from a laser beam, and then re-emit photons in random directions, undergoing a net increase in momentum in the incident photon direction. Because of the Doppler effect, this force is velocity dependent. It has typically been used to dissipate the atom's energy in laser cooling and trapping experiments. The second, or dipole force, comes from the interaction between a gradient in the laser intensity and an induced electric dipole moment in the atom. In our experiments, a dissipative radiation pressure effect is used to enhance the brightness and collimate a Cr atom beam, and then the dipole force is used to focus the atoms before they impinge on the substrate.

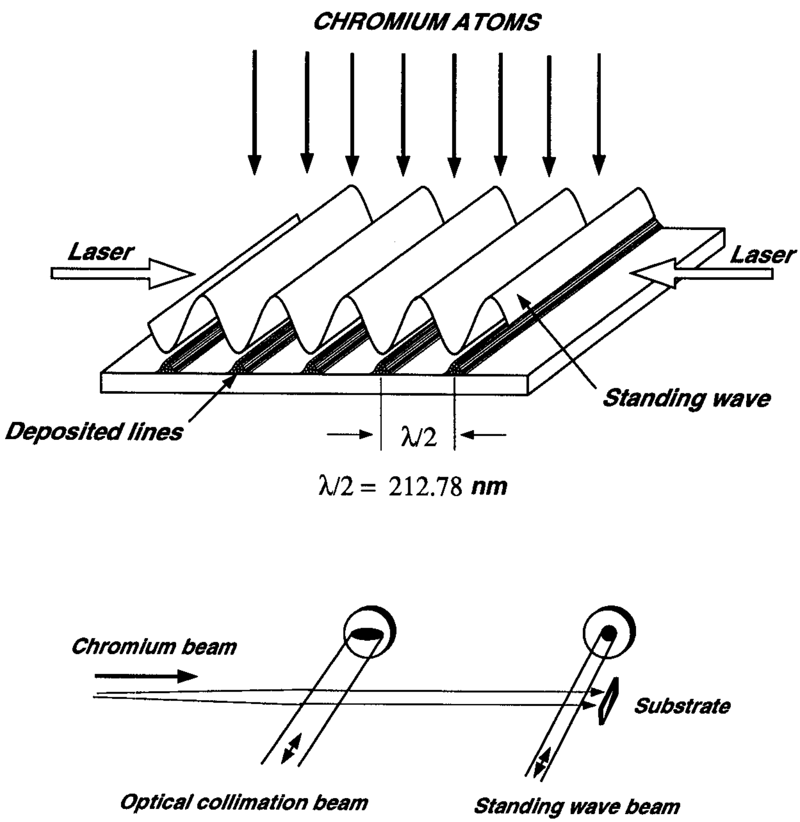

Figure 1 Laser standing wave configuration above substrate showing deposition scheme (top); overview showing the collimation and deposition regions (bottom).

This implementation of atom optics techniques for nanostructure fabrication uses a laser-generated standing wave positioned just above a Si substrate to give rise to periodic variations in light intensity. A series of cylindrical lenses is created, spaced by $\lambda/2$ or 212.78 nm, which focus the atoms into lines on a Si substrate. The wavelength, λ, is chosen to correspond to a resonance transition in Cr to maximize the effect of the dipole force. The laser is tuned 198 MHz above the atomic resonance to reduce the effect of spontaneous emission. Since the periodic potentials that form the individual lens elements are not very strong, it is essential for the atoms entering the standing wave region to have very low velocities transverse to the surface normal, i.e. along the standing wave. This is accomplished by first passing the collimated beam through a region where radiation pressure is used to reduce the atoms' transverse velocity. Counter-propagating laser beams with a frequency 5 MHz lower than the Cr resonance line are used. Each laser beam is linearly polarized and their planes of polarization are mutually perpendicular. This process produces an atom beam collimation of less than 0.2 mrad (FWHM), sufficient for capture by the standing wave lenses.

4. Results

An atomic force micrograph of a Cr nanostructure fabricated by this method is shown in Fig. 2. A uniform pattern of parallel lines, replicating the standing wave spacing of 212.78 nm, was observed over a 0.5 mm x 1.0 mm area of a Si substrate using both scanning electron microscopy and atomic force microscopy. The AFM measurements showed lines approximately 34 nm high with a breadth of 65 nm (FWHM), uncorrected for broadening due to the shape of the AFM tip itself.

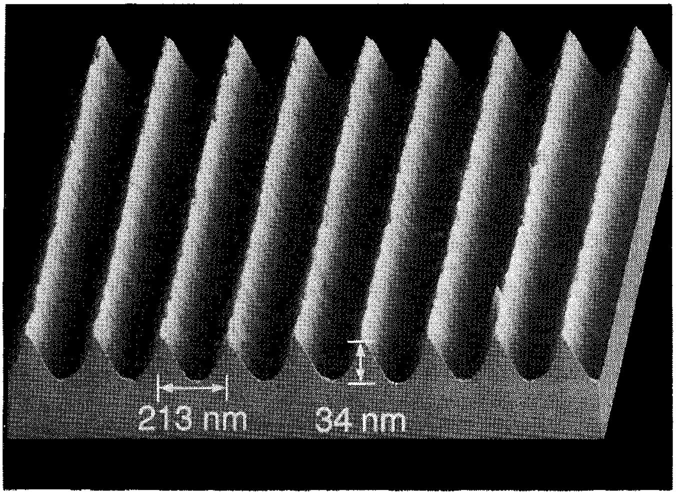

Figure 2 An AFM topograph of a typical 2 μm by 2 μm region of Cr lines fabricated by laser-focused atom deposition.

5. Discussion

The fabrication of a permanent Cr nanostructure using atom optical technology constitutes a first step toward a more general application of the technique. The current observed line width of 65±6 nm (uncorrected) is substantially larger than our models predict will ultimately be available. While the de Broglie wavelength associated with the atoms is about 8 pm, the small convergence angle of the lens suggests that the diffraction limit should be about 9 nm [1]. Other line broadening mechanisms include the residual atom beam divergence, and the spherical and chromatic aberrations of the lens elements. The resolution can be improved by shortening the focal length, by monochromatizing the atom beam and by, possibly, using a different lensing potential.

Future work efforts will go toward generalizing the method. For example, the period of the standing wave currently fixes the periodicity of the pattern. Techniques, e.g. standing waves generated from inclined laser beams, will be devised to increase the distance between lens centers. Also, the technique will be generalized to produce a two dimensional pattern through the superposition of standing wave patterns at right angles. Such a pattern can produce either a field of crossed perpendicular lines (already seen by us in preliminary experiments) or spots, depending on the standing wave laser frequency. The geometry that produces spots can be envisioned as an array of lenses, capable of depositing atoms on a surface, with 10 nm resolution, at equally spaced intervals in two dimensions. The surface could then be translated under this lens array to write an arbitrary pattern that is reproduced at equally spaced intervals in a massively parallel fashion. Applications include nanostructure fabrication, either by direct deposition, by undercoating, or via resist exposure using focused metastable atoms, and length standards for lithography and microscopy.

ACKNOWLEDGEMENTS

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